

SYNTHESIS AND CHARACTERIZATION OF NANOPARTICLE INCORPORATED
POLYMER COMPOSITE MATERIALS

MD. NAJMUL KABIR CHOWDHURY

Thesis submitted in fulfilment of the requirements for the award of the degree of
Doctor of Philosophy in Chemical Engineering

Faculty of Chemical and Natural Resources Engineering

UNIVERSITI MALAYSIA PAHANG

April 2014

ABSTRACT

This thesis is composed with the aim of the synthesis of nanoparticle impregnated oil palm fibre reinforced composites. This aim is initiated with the synthesis of copper nanoparticles (CuNPs) at ambient condition in aqueous medium using copper chloride precursor, sodium borohydride (SBH), ascorbic acid and polyvinyl alcohol (PVA) of two different molecular weights (M_w s). The formation and characterization of the nano copper sols are studied. The physical appearance of prepared sol has been found to be stable for a couple of weeks when kept in ambient atmospheric condition, as confirmed by ultraviolet-visible absorption spectroscopy. Transmission electron microscopy exhibits spherical morphology of CuNPs with an average size of 3.5 ± 1.1 nm. The effect of SBH amount and PVA (wt.% and M_w s) on the size of CuNPs are also delineated. As a potential application of CuNPs, they were impregnated on/into oil palm empty fruit bunch (EFB) fibres via cationization process. Conventionally, same EFB fibres were also treated with alkali solutions. Treated fibres were characterized by Fourier transformed infrared (FTIR) spectroscopy, X-ray diffraction (XRD) study, field emission scanning electron microscopy (FESEM), energy dispersive X-ray (EDX) study and thermogravimetric analysis (TGA). Numerous physical and mechanical properties of different single fibres were measured and especially the mechanical properties were analyzed by the Griffith model and Weibull statistical distribution. The weak link scaling of Weibull analysis has provided valuable information to scale the strength of one EFB fibre to predict the strength of other one. A significant increase in mechanical property of CuNPs modified fibres with respect to the control ones has been observed. CuNPs impregnated EFB fibres show increases of tensile strength (~34%) and antifungal activity (24%) with respect to control fibres. These findings strongly suggest that CuNPs can be used as an effective agent in natural fibres to improve their mechanical property and durability. Therefore, different doses CuNPs impregnated strong and durable fibres were used to develop the CuNPs impregnated fibre reinforced unsaturated polyester resin nanocomposite. The composite behaviour, mechanical property and biodegradability have been investigated systematically by using the commonly used techniques such as FTIR, XRD, FESEM, TGA, differential scanning calorimetry (DSC), universal tensile testing tester, etc. The developed nanocomposites mechanical properties and biodegradability were optimized by response surface methodology (RSM) also. The biodegradability of the developed composites was inversely proportional to the CuNPs loadings. The change of weight gain (due to moisture absorption) for all samples is highly related with a typical Fickian diffusion behaviour. Moreover, higher mechanical (tensile and flexural) performances were obtained for CuNPs treated fibre (NF) composites compared to those of untreated fibre based composites. Among all of the fibre reinforced composites tested, NF reinforced unsaturated polyester resin composites (30% fibre) registered for the highest mechanical properties. It was found that standard micromechanical models (Rule of Mixture, Inverse Rule of Mixture and Halpin-Tsai Model) which are commonly used to predict the strength of traditional synthetic fibre composites can be applied to such natural fibre systems with mixed success. Throughout the work, three schemes were proposed. The obtained properties of the developed nanocomposites indicate that they can be considered for both indoor-outdoor applications.

ABSTRAK

Tesis ini di jalankan bertujuan untuk memperbangunkan komposit yang di perkukuhkan dengan gentian minyak sawit bersaiz nano. Matlamat ini dimulakan dengan mensintesis nano-zarah kuprum (CuNPs) pada keadaan ambien di dalam medium akueus menggunakan kuprum pelopor klorida , natrium borohydride (SBH), asid askorbik dan alkohol polyvinyl (PVA) pada dua berat molekul yang berbeza (MWS). Pembentukan dan pencirian sols kuprum nano telah dikaji. Penampilan fizikal sol didapati stabil selama beberapa minggu apabila disimpan dalam keadaan atmosfera ambien setelah disahkan oleh spektroskopi penyerapan ultraviolet. Transmission electron microscopy mempamerkan morfologi sfera untuk CuNPs dengan saiz purata bernilai 3.5 ± 1.1 nm. Kesan daripada jumlah SBH dan PVA (wt. % dan MWS) pada saiz CuNPs juga ditandakan. Sebagai satu aplikasi CuNPs yang berpotensi, sampel tersebut telah di terapkan pada minyak gentian tandan kelapa sawit (EFB) melalui proses cationisasi. Secara formalnya, gentian EFB tersebut dirawat dengan rawatan alkali. Gentian yang telah dirawat dianalisis oleh Fourier transformed infrared (FTIR) spectroscopy, X-ray diffraction (XRD) study, field emission scanning electron microscopy (FESEM), energy dispersive X-ray (EDX) study dan thermogravimetric analysis (TGA). Sifat-sifat fizikal dan mekanikal gentian tunggal yang berbeza telah diukur terutamanya menggunakan sifat-sifat mekanikal yang dianalisis oleh model Griffith dan Weibull pengagihan statistik. Pautan bersisik lemah analisis Weibull telah memberikan maklumat yang penting kepada skala kekuatan satu gentian EFB untuk meramalkan kekuatan gentian EFB yang lain. Peningkatan yang ketara dalam sifat mekanikal gentian CuNPs diubahsuai mengikut sample kawalan. Penerapan CuNPs kepada gentian EFB menunjukkan peningkatan kekuatan tegangan sebanyak (~ 34%) dan aktiviti antikulat sebanyak (24%) berkenaan dengan mengawal gentian. Penemuan ini mencadangkan bahawa CuNPs boleh digunakan sebagai agen berkesan dalam gentian asli untuk meningkatkan sifat mekanik dan ketahanan. Oleh itu, dos CuNPs yang berlainan menghasilkan gentian kuat dan tahan lama telah digunakan untuk menghasilkan damar nanokomposit poliester tidak tepu yang diperkukuhkan dengan gentian yang diterap dengan CuNPs. Sifat-sifat komposit seperti, sifat mekanikal dan biodegradasi telah disiasat secara sistematik dengan menggunakan teknik-teknik yang biasa digunakan seperti FTIR , XRD, FESEM , TGA , kalorimetri imbasan pembeza (DSC), mesin ujian universal, dan lain-lain lagi. Sifat mekanik dan biodegradasi nanokomposit adalah dioptimumkan dengan menggunakan response surface methodology (RSM). Sifat biodegradasi komposit adalah berkadar songsang dengan bebanan CuNPs. Perubahan jisim (disebabkan oleh penyerapan kelembapan) bagi semua sampel berkait rapat dengan tingkah laku penyebaran Fickian . Selain itu , prestasi mekanikal yang lebih tinggi (tegangan dan lenturan) telah diperolehi untuk serat yang dirawat oleh CuNPs (NF) komposit berbanding dengan komposit berasaskan gentian yang tidak dirawat. Antara semua komposit yang diperkukuhjkn oleh gentian diuji, komposit resin poliester yang diperkukuhkan oleh NF (30% serat) dikenalpasti memperoleh sifat-sifat mekanik tertinggi. Ia telah didapati bahawa piawaian model mikro mekenikal (Rule of Mixture, Inverse Rule of Mixture and Halpin-Tsai Model) yang biasa digunakan untuk meramalkan kekuatan komposit gentian sintetik tradisional boleh digunakan untuk sistem gentian semula jadi dengan jayanya. Sepanjang kerja ini, tiga

skim telah dicadangkan. Sifat-sifat yang diperolehi daripada kemajuan nano-komposit menunjukkan bahawa ia boleh dipertimbangkan untuk kedua-dua aplikasi dalaman-luaran.

TABLE OF CONTENTS

THESIS CONFIDENTIAL STATUS	ii
SUPERVISOR'S DECLARATION	v
STUDENT'S DECLARATION	vi
ACKNOWLEDGEMENTS	vii
ABSTRACT	viii
ABSTRAK	ix
TABLE OF CONTENTS	xi
LIST OF TABLE	xix
LIST OF FIGURES	xxi
LIST OF ABBREVIATIONS	xxiv
CHAPTER 1	1
INTRODUCTION	1
1.1 OVERVIEW	1
1.2 PROBLEM STATEMENT	11
1.3 OBJECTIVES	11
1.4 SCOPE OF THE STUDY	12
1.5 NOVELTY OF THE WORK	13
CHAPTER 2	15
LITERATURE REVIEW	15
2.1 BACKGROUND OF NANOTECHNOLOGY	15
2.2 POTENTIAL MARKET OF NANOTECHNOLOGY	17
2.3 NANOMATERIALS AND THEIR APPLICATIONS	17

2.4 PREPARATION OF METALLIC PARTICLES IN SOLUTIONS.....	18
2.4.1 Reduction Mechanism	18
2.4.2 Effect of Reaction Medium (Solvent).....	20
2.4.3 Particle Formation Mechanism	21
2.4.4 Particle Shape, Structure and Size	23
2.5 COMMON METHODS OF NP SYNTHESIS.....	24
2.5.1 Chemical Methods	25
2.5.1.1 Chemical reduction method	25
2.5.1.2 Micro-emulsion/colloidal method	27
2.5.1.3 Sonochemical method	28
2.5.1.4 Microwave method.....	29
2.5.1.5 Electrochemical method.....	29
2.5.1.6 Solvothermal decomposition.....	30
2.5.2 Physical Methods	31
2.5.2.1 Pulse laser ablation/deposition	31
2.5.2.2 Mechanical/ball milling method.....	31
2.5.3 Mechanochemical Synthesis	32
2.5.4 Biological Synthesis.....	32
2.6 CONCISE OF SYNTHESIS METHODS	33
2.7 POSSIBLE TECHNIQUES TO OVERCOME THE OBSTACLES OF NPs SYNTHESIS.....	38
2.7.1 Support for Synthesis	39
2.7.2 Polymeric Materials and Surfactants as Stabilizers for NPs.....	40
2.7.3 Coating Materials.....	41

2.8 CHARACTERIZATION OF NPs	43
2.9 PERFORMANCE OF NPS AND THEIR FABRICATED MATERIALS	44
2.9.1 Antimicrobial Purposes	45
2.9.2 Surface Modification and Fabrication by NPs	46
2.10 OIL PALM FIBRE (OPF)	48
2.10.1 Extraction Processes	48
2.10.2 Properties of OPF	48
2.10.3 Surface Treatments for Making Better Composite	53
2. 11 OIL PALMS BIO-PRODUCTS	56
2.12 OIL PALM FIBRE COMPOSITES	58
2.13 Oil Palm Fibre-Polyester Composites	59
2.14 POLYMER NANOCOMPOSITES WITH NPs	60
2.14.1 Physical Properties of Nanocomposites	61
2.14.1.1 Effect of fibre loading	61
2.14.2 Mechanical Properties	62
2.14.2.1 Effect of fibre loading	62
2.14.2.2 Effect of fibre treatments	63
2.14.3 Water Absorption Characteristics	64
2.14.3.1 Effect of fibre loading	64
2.14.3.2 Effect of fibre treatments on water absorption	64
2.14.4 Degradation Due to Weathering	65
2.14.4.1 Effect of fibre loading	65
2.14.4.2 Effect of fibre treatment	65
2.15 MODELING FOR SINGLE FIBER AND COMPOSITE	67

2.15.1 Preliminary Theory on Weibull Statistics.....	67
2.15.2 Perspectives of Micromechanical Models	69
2.15.3 Rule of Mixtures Equation.....	69
2.15.4 Inverse Rule of Mixtures Equation	70
2.15.5 Halpin–Tsai Equation	71
CHAPTER 3	73
MATERIALS AND METHODS.....	73
3.1 INTRODUCTION.....	73
3.2 MATERIALS	74
3.2.1 List of Chemicals	74
3.2.2 Matrix.....	75
3.2.3 Fiber	75
3.3 METHODS	75
3.3.1 Preparation of Nanocopper Sols	75
3.3.2 Modifications of EFB Fibres.....	76
3.3.2.1 Alkali treatment	76
3.3.2.2 Cationization of fibres	76
3.3.2.3 Impregnation of CuNPs in CFs	76
3.3.3 Weight Loss and Moisture Content Study	77
3.3.4 Diameter and Aspect Ratio	77
3.3.5 Antimicrobial Activity of Single Fibres	78
3.3.5.1 Antibacterial activity	78
3.3.5.2 Antifungal activity	78
3.3.6 Development of Composites.....	78

3.3.7	Characterization Techniques	80
3.3.7.1	Ultraviolet-visible absorption spectroscopy	80
3.3.7.2	Fourier transformed infrared spectroscopy.....	80
3.3.7.3	Atomic Absorption Spectrophotometry.....	81
3.3.7.4	Determination of pH at zero point charge	81
3.3.7.5	Transmission and scanning electron microscopy	81
3.3.7.6	Mechanical properties of single fibres and composites.....	82
3.3.7.7	Thermogravimetric analysis of single fibres and composites	83
3.3.7.8	Differential scanning calorimetric analysis of composites	83
3.3.7.9	X-ray diffraction analysis.....	83
3.3.7.10	Water absorption behaviour of composites	84
3.3.8	Biodegradability of Composites	85
CHAPTER 4	88
RESULTS AND DISCUSSION	88
4.1	INTRODUCTION.....	88
4.2	SYNTHESIS OF NANO COPPER SOLS WITH DIFFERENT REDUCING AGENTS	89
4.3	CHARACTERIZATION OF SOLS.....	91
4.3.1	UV-Vis Spectroscopic Characterization	91
4.3.1.1	UV-Vis absorption spectra of copper sols.....	91
4.3.1.2	Formation Rate of CuNPs.....	93
4.3.1.3	Stability of CuNPs	94
4.3.1.4	Effect of sodium borohydride on synthesis	96
4.3.2	Characterization of Sols by FTIR Spectroscopy	97

4.3.3 Characterization of Sols by TEM	99
4.3.3.1 Effect of the concentration of precursor.....	99
4.3.3.2 Effect of molecular weights of PVA	101
4.3.3.3 Effect of the concentration of sodium borohydride	102
4.4 PREPARATION AND CHARACTERIZATION OF CuNPs LOADED FIBRES	103
4.4.1 Impregnation of CuNPs from Sols in Untreated EFB Fibres	103
4.4.2 Characterization of as Prepared CuNPs Sol Treated Fibres	104
4.4.3 Using Concentrated CuNPs Sol	105
4.4.4 Alternative Way of Impregnation and Its Characterization.....	106
4.4.4.1 Fibre surface modification by cationic agent	106
4.4.4.2 Characterization of CFs by FTIR	107
4.4.4.3 Determination of pH_{pzc} of UF and CF	109
4.4.4.4 Effect of CuNPs sol concentration on copper loading in CF	110
4.4.4.5 Surface Morphology of fibres	112
4.5 PROPERTIES OF DIFFERENT SINGLE FIBRES	113
4.5.1 Physical Parameters of AFs	114
4.5.1.1 Weight loss and moisture content.....	116
4.5.1.2 Diameter and aspect ratio	116
4.5.2 Surface Morphology of Untreated and Alkali Treated Fibres	119
4.5.3 FTIR Analyses of Untreated and Alkali Treated Fibres	119
4.5.4 Mechanical Properties of Different Single Fibres	120
4.5.4.1 Analysis with Griffith Model	122
4.5.4.2 Weibull distribution.....	124

4.5.5 Thermal Properties of Different Single Fibres.....	129
4.5.6 X-Ray Diffractograms of Different Single Fibres	131
4.5.7 Antimicrobial Performances	133
4.5.7.1 Antibacterial performances of CuNPs in fibres	133
4.5.7.2 Antifungal performances of CuNPs in fibres	135
4.6 DEVELOPMENT OF NANOCOMPOSITE	137
4.6.1 Characterization of Developed Nanocomposite	137
4.6.1.1 FTIR study of composites.....	137
4.6.1.2 Interfacial adhesion of EFB/unsaturated polyester resin composite	140
4.6.2 Effect of Fibre Loading on Mechanical Performances of Composites	141
4.6.3 Charpy Impact Strength	146
4.6.4 Thermal Properties of Composites.....	147
4.6.4.1 Thermogravimetric analysis	147
4.6.4.2 DSC of composites.....	150
4.6.5 XRD Analysis	152
4.6.6 Water Absorption of Composites.....	153
4.6.7 Theoretical Modeling of Composites.....	155
4.6.8 Biodegradability of the Composites.....	158
4.6.8.1 Response surface methodology (RSM) design.....	158
4.6.8.2 Validation of empirical model adequacy	166
4.6.8.3 Process optimization.....	167
CHAPTER 5	168
CONCLUSION AND RECOMMENDATIONS	168
5.1 CONCLUSION	168

5.2 RECOMMENDATIONS FOR FUTURE WORK	170
REFERENCES	171
APPENDIX.....	215
LIST OF PUBLICATIONS	215

LIST OF TABLE

Table 2.1: Selection of reducing agents and reaction conditions in the synthesis of metal particles (Goia and Matijevic, 1998)	20
Table 2.2: List of published methods to synthesize CuNPs by chemical reduction	26
Table 2.3: A critical review on the synthesis techniques of CuNPs	35
Table 2.4: A summary of characterization techniques.....	43
Table 2.5: Constituents of OPF (Shinoj et al., 2011).....	49
Table 2.6: Physico-mechanical properties of OPF	51
Table 2.7: Effect of surface treatments on properties of OPF	55
Table 2.8: The mechanical properties of OPF-polyester and OPF-polyester-glass fibre composites at different fibre contents (Shinoj et al., 2011).	62
Table 3.1:List of chemicals used in this work.	74
Table 3.2: Variables for model (screening design)	86
Table 4.1: Concentration of Cu in sols before and after dipping of fibres	104
Table 4.2: Concentration of Cu before and after dipping of fibres in concentrated sols.	106
Table 4.3: Adsorptions of copper on CF from different concentrations of sols	110
Table 4.4: Physical parameters of EFB fibres obtained after alkali treatment with different concentrations and soaking times.	115
Table 4.5: Parameters for the Griffith model obtained from UF and AF of different lengths.	124
Table 4.6: Parameters for Weibull distribution model and the estimated percentage of deviation, $\Delta\sigma$ %, for differently treated fibres of various lengths.....	128
Table 4.7: Amount of moisture removal, T_o , T_d at 50% WL and residue content at 580 °C for UF, AF (0.5-5.0% and 24 h) and AF (1-48 h, 0.5%) along with CF fibres and NF.	131
Table 4.8: Crystalline parameters obtained from XRD diffractograms of different treated EFB fibres.	133
Table 4.9: Antimicrobial performances of synthesized CuNPs in EFB fibres	134
Table 4.10: Thermogravimetric parameters of virgin resin and the composites	150

Table 4.11: The parameters of virgin resin and the composites obtained from DSC analysis.....	151
Table 4.12: Water absorption performance of virgin resin and composites	155
Table 4.13: Calculated and best-fit values of ξ	157
Table 4.14: Experimental layout and results of D-optimal design	159
Table 4.15: ANOVA for Response Surface Quadratic Model; response: Biodegradability (%).....	160
Table 4.16: Validation of the model obtained from RSM	166

LIST OF FIGURES

Figure 2.1: Basic depiction of one-directional stresses for fibre and matrix of the composite.	70
Figure 2.2: Basic depiction of two-directional stresses for fibre and matrix of the composite.	71
Figure 3.1: Used stainless steel mold for making composites sheet	79
Figure 4.1: Obtained sols using with: (a) lower alcohols (1: precursor solution; 2-4: Methanol-Propanol) and (b) DMSO.	89
Figure 4.2: Copper sols with different molar ratio (mr) of sodium borohydride to precursor: (a) 0, (b) 0.5, (c) 1.0, (d) 1.2, (e) 1.3, and (f) 1.75.	90
Figure 4.3: The UV-VIS spectra of (a) Cu^{2+} solution and (b) nanocopper sol at initial stage of synthesis.	92
Figure 4.4: Evolution of normalized absorbance of Cu nanoparticles during the synthesis (maximum absorbance at 516 nm is used for normalization).	93
Figure 4.5: (i) CuNPs sols: (a) at initial stage, (b) after 14 days, and (c) after 16 days of ... synthesis; (ii) The UV-VIS spectra of nanocopper sols (a) at initial stage, (b) after 10 mins, and (c) after 16 days of synthesis	95
Figure 4.6: Effect of sodium borohydride to precursor molar ratios on CuNPs synthesis	97
Figure 4.7: FTIR spectra of nanocopper sols: before (S1) and after (S2) NP formation ..	98
Figure 4.8: TEM images of CuNPs observed from different sols: (a) 50 (b) 100 (c) 250 mg CuCl_2 with PVA of Mw = 70000, and (d) 100 mg CuCl_2 with PVA of Mw = 2000.	100
Figure 4.9: Histogram for showing the size (number average) distribution of the synthesized CuNPs (from Figure 4.8(a)-(c)).	101
Figure 4.10: Effect of sodium borohydride concentration on the size of CuNPs: (a) 7.4 mL, (b) 8.0 mL, (c) 9.3 mL, and (d) 10.6 mL of NaBH_4 solution.	103
Figure 4.11: XRD patterns of different fibres: a) UF and b) NF	105
Figure 4.12: FTIR spectra of (a) UF and CF, and (b) extended form at $1500\text{--}1400\text{ cm}^{-1}$ for the same fibres.	108
Figure 4.13: Surface charge of fibres as a function of pH: (a) UF and (b) CF.	110

Figure 4.14: FTIR spectra of CF and NF.	112
Figure 4.15: Surface morphologies and the EDX profiles of NFs: (a-c) FESEM images of NF, (d-e) EDX spectra of the marked zone of (b) and (d), respectively, (f-g) EDX profiles of (d) and (e), respectively.	113
Figure 4.16: SEM images of (a) UF, and (b) AF 24	119
Figure 4.17: FTIR spectra of UF (a), AF at 1 h (b), 6 h (c), 12 h (d), 24 h (e) and 48 h (f).	120
Figure 4.18: (i) The stress-strain plots of some UF of length 30 mm and diameters (a) 0.31, (b) 0.28, (c) 0.22, (d) 0.16, and (e) 0.12 mm and (ii) soaking-time dependent average tensile-strength of lengths (a) 30, (b) 50 and (c) 70 mm for UF.	121
Figure 4.19: Tensile strength/modulus versus diameter plots: for fibres of lengths (i) 10 (ii) 50 mm. Δ and \blacktriangledown are observed values; — (a) and ... (b) are indicating the Griffith plots.	123
Figure 4.20: (i) Weibull plots for the UFs of lengths (a) 30, (b) 50 and (c) 70 mm, and (ii) Weak link scaling plots with lengths (a) 30, 50 mm, (b) 30, 70 mm and (c) 50, 70 mm of UFs.	127
Figure 4.21: TGA thermograms of (a) UF and AF obtained with various concentration of alkali, and (b) EFB fibres treated at different soaking times, CF and NF.	130
Figure 4.22: Wide-angle XRD profiles of UF (a), AF at 1 h (b), 6 h (c), 12 h (d), 24 h (e) and 48 h (f), CF (24 h) (g), and NF (24 h).	132
Figure 4.23: Tensile strengths of UF and NF before burial (BB) and after burial (AB) under soil at different days of exposition: (i) after 7 days, and (ii) after 30 days.	136
Figure 4.24: FTIR spectra of: (a) virgin resin, (b) UF and (c) NF reinforced composite	138
Figure 4.25: FESEM micrographs of the fractured surface of (a) UF-C and (b) NF-C..	141
Figure 4.26: Effect of fibre loading on (i) tensile strength and (ii) tensile modulus of the composites: (a) UF-C, (b) CF-C, and (c) NF-C.	142
Figure 4.27: Effect of fibre loading on (i) flexural strength and (ii) flexural modulus of : (a) UF-C, (b) CF-C, and (c) NF-C.	145
Figure 4.28: Charpy impact strengths of virgin resin and different fibre (30% loading) reinforced polyester resin composites.	146

Figure 4.29: TGA curves for: (a) VR, (b) UF-C and (c) NF-C.....	148
Figure 4.30: DTG curves for VR (a), UF-C (b) and NF-C (c).	150
Figure 4.31: DTA curves for virgin resin (VR), untreated EFB fibre reinforced composite (UF-C) and CuNPs impregnated fibre composites (NF-C)	151
Figure 4.32: XRD pattern of: (a) VR, (b) UF-C, (c) CF-C, and (d) NF-C.....	153
Figure 4.33: Water absorption performances of virgin polyester resin (a), untreated (b) and treated (c) fibre–reinforced composites.	154
Figure 4.34: Determination of composites' modulus containing (i) UF and (ii) NF: where, (a) experimental data, (b) ROM, (c) IROM, and (d) Halpin-Tsai.	156
Figure 4.35: Normal probability plot of residual for biodegradability of composites. ...	163
Figure 4.36: Plot of residual against predicted response for biodegradability of composites.....	163
Figure 4.37: Interaction graph (a) and contour plot (b) for biodegradability of composites from the model equation: effect of A and B.	164
Figure 4.38: 3D surface presentations of responses due to the effect of factors.....	165

LIST OF ABBREVIATIONS

AAS	Atomic absorption spectroscopy
AATCC	American Association of Textile Chemists and Colourists
AB	After burial
AF	Alkali treated EFB fibre
AFM	Atomic force microscopy
AMA	Allyl methacrylate
ANOVA	Analysis of variance
ASTM	American Standard Testing Method
BB	Before burial
BD	Biodegradability
C	Degree of cationization
CF	Cationized EFB fibre
CF-C	CF reinforced composite
CHPTAC	3-Chloro-2-hydroxypropyl)trimethylammonium chloride
CRP	Chemical reduction process
CRP	Chemical reduction process
CTAB	Cetyltrimethylammonium bromide
Cu	Copper
CuNPs	Copper nanoparticles

D	Coefficient of diffusion,
D_{hkl}	Average size of the cellulose crystallites
d	Diameter
DEG	Di-ethylene glycol
DI	Deionized water
DMSO	Dimethyl sulfoxide
DSC	Differential scanning calorimetry
DTG	Differential thermo gravimetry
E	Moment of inertia of the composite beam
E. coli	Escherichia coli
EB	Elongation at break
EDX	Energy dispersive X-ray
E_F	Elastic modulus of fibre
EFB	Empty fruit bunch
E_M	Elastic modulus of matrix
F	Faraday's constant
FESEM	Field emission scanning electron microscopy
FTIR	Fourier transformed infrared
FWHM	Full width at half-maximum
G	Modulus of rigidity

GDI	Gasoline Direct Injection
GHz	Gigahertz
GPa	Giga Pascals
HDEHP	Bis(ethylhexyl)hydrogen phosphate
HMP	Hexameta phosphate
IROM	Inverse rule of mixing
K	Equilibrium constant
kHz	kilohertz
l	Span of the composite beam
L	Length
MC	Moisture content
MDF	Medium density fibre
MHz	Megahertz
M_m	Moisture content at saturation point
MNP	Metal nanoparticles
MOP	Molded oil palm
MPa	Mega Pascal
MRSA	Methicillin-resistant Staphylococcus aureus
M_w	Molecular weight
m_w	Weibull modulus

NF	Nanosol treated EFB fibre
NF-C	NF reinforced composite
NFRT	Natural fibre reinforced thermoplastic
nm	Nanometer
NP	Nanoparticle
NPs	Nanoparticles
NR	Natural rubber
OPA	Oil palm ash
OPF	Oil palm fibre
OPFr	Oil Palm Fronds
OPT	Oil Palm Trunk
P	Load within the elastic range
PAA Na	Polyacrylic acid sodium salt
PCS	Photon correlationspectroscopy
PEG	Polyethylene glycol
PEI	Polyethylene imine
PF	Phenol formaldehyde
P_f	Probability of failure
PLA	Poly(lactic acid)
PP	Polypropylene
pp	Particles

ppm	Parts per million
PU	Polyurethane
PVA	Polyvinyl alcohol
PVC	Polyvinyl chloride
PVP	Polyvinylpyrrolidone
PWD	Pulsed wire discharge
PZC	Zero point charge
R	Gas constant (J/mol K)
RC	Regenerated Cellulose
ROM	Rule of mixing
RSM	Response surface methodology
S. aures	Staphylococcus aureus
SBH	Sodium borohydride
SDS	Sodium dodecyl sulfate
SEM	Scanning electron microscope
SPR	Surface plasmon resonance
SS	Sodium succinate
T	Temperature (in Kelvin)
t	Treatment time
T ₀	Onset temperature
T _c	Crystallization Temperature (°C)

TCF	Total chlorine-free
T _d	Degradation temperature
TEM	Transmission electron microscopy
TEPA	Tetraethylenepentamine
T _g	Glass Transition Temperature (°C)
TGA	Thermo gravimetric analysis
T _m	Melting endotherm
T _m	Melting Temperature (°C)
TM	Tensile modulus
TOAB	Tetraoctylammonium bromide
TS	Tensile strength
TX-100	Triton X-100
UF	Untreated EFB Fibre
UF-C	UF reinforced composite
USA	United States of America
UV-vis	Ultra-violet visible
V	Volt
V _F	Volume fraction of fibre
V _M	Volume fraction of matrix
VR	Unsaturated polyester resin
W _f	Weight of fibre
WL	Weight loss

W_m	Weight of matrix
XRD	X-ray diffraction
Y	Young's modulus
β	FWHM (in radians)
ΔE	Redox potential
ΔH	Heat of fusion (J/g)
θ	Diffraction angle
λ	Wavelength of X-ray (1.541 Å)
ρ_f	Density of fibre
ρ_m	Density of matrix
σ_{ave}	Average tensile strength
∂	Total deflection
ΔG^0	Gibb's free energy
μg	Microgram
μm	Micrometer
2θ	Scattering angle